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SELECTED REVIEW OF METHODOLOGIES IN FREIGHT TRANSPORTATION PLANNING

by

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ABSTRACT

The scope of this report is to present a set of mathematical programming methodologies pertinent to the tactical and strategic planning of freight transportation, as well as some of the important work done in this domain. We cover supply modelling (cost, tariff and energy consumption models), demand modelling and modal choice models, distribution problems, intermodal systems and terminals, as well as models for the planning of freight transportation by rail. There is also a section dedicated to models for national planning in developing countries.

RÉSUMÉ

Dans ce rapport, nous présentons un ensemble de méthodologies de programmation mathématique pertinentes à la planification tactique et stratégique du transport des marchandises, ainsi qu'une compilation des principaux travaux dans ce domaine. Nous examinons les modèles d'offre (coûts, tarfis, consommation d'énergie), de demande de choix modal et de distribution, ainsi que les modèles pour les systèmes de transport intermodaux, y inclus les terminaux. Le rapport est complété par un chapitre sur des modèles de transport ferroviaire des marchandises et par un autre sur les modèles de planification nationale dans les pays en voie de développement.

INTRODUCTION

A study of existing methodologies pertinent to freight transportation planning is a difficult task because of the heterogeneity of commodities and shippers and the differences in the quality and reliability of the various modes of transport which may be involved.

In an attempt to determine the extent and relevance of the existing literature to the joint project entitled : "Energy consumption by freight transportation in Brazil : Strategic planning and policy evaluation", we will consider four main freight transportation research areas. These topics are not totally unrelated, nor do they cover all transportation issues exhaustively :

- Transportation supply modelling
- Freight transportation demand modelling
- Physical distribution
- Intermodal systems.

Transportation supply modelling involves mainly models for quantifying carrier and terminal operating costs, carrier energy consumption, freight tariff rates, and the levels of service. Aggregate cost and energy consumption models are abundant in the literature, while models for freight tariff rates are rather scarce. This is due to the fact that, in general, it is extremely complex to structure the rationale behind various set of tariff rates. Tariff rates depend strongly on the attributes of the commodity, they often vary from one origin-destination pair to another and they embody many exception rules and subtle applications. The measurement of the level of service of the carrier is as important as its tariff rates and operating costs. The identification of the service variables and their estimation are discussed in the modal choice review.

Demand modelling involves three major areas : demand generation, distribution of freight demand and modal choice. These models, which can be divided into optimization modelling and empirical modelling approaches, will be discussed in some detail.

From the point of view of the firm, the freight transportation process is a physical distribution process. The firm is mainly concerned with production planning, inventory control, warehousing, transportation and marketing. The emphasis here is placed on the strategic planning aspects of physical distribution involving decisions related mainly to warehouse location and to the transportation problem of establishing routes from the factory through the warehouse to the client. Tactical planning concerning the routing and scheduling of vehicles and crews will not be considered here. For a detailed review of these subjects we recommend the survey by Bodin et al. (1983)[1].

The economics of freight transportation sometimes requires the combination of several modes of transportation which constitute an intermodal system. The three major components of an intermodal system are the local service, the linehaul and the terminal system. The local service component, using small capacity vehicles serves the regional shippers and consignees. Examples are trucks that carry pick-up and delivery shipments to and from shippers or consignee loading terminals. The linehaul component encompasses trucks, trains or boats which carry shipments over significant distances to their destination. At the destination terminals, shipments are again the responsibility of the local

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[1] Bodin, L., Golden, B., Assad, A., and Ball, M. (1983) "Routing and Scheduling of Vehicles and Crews. The State of the Art.", Computers and Operation Research 10, 2 (Special issue).

service component. Examples of existing intermodal systems are the truck on rail flat car (TOFC) system, the container on rail flat car (COFC) system and the marine container system. The interrelationships between the components of the intermodal system are the main issues discussed in the literature.

On a larger scale, the study of intermodal systems for freight transportation focuses on the linehaul aspects of the transportation modes available in the region. The intermodal system is then composed of mode-dedicated or intermodal transshipment terminals and modal linehaul links between them, while models in this category aim at finding routes for the traffic through this system and compute volumes, costs, modal splits, etc. This type of models are often related to national or regional transportation studies.

In addition to these general subject areas, we will also discuss rail freight transportation in some detail. The reason for singling out this mode is as follows : The rail mode in Brazil accounts for only 18% of the total ton-km in freight shipments. This tonnage is well under the 70% carried by the less energy efficient truck mode. Therefore, seeking to increase the market share of the rail mode in freight transportation is likely to achieve a more efficient use of energy in the transport sector.

Finally, the last section of this document is an overview of some existing national transportation models for developing countries.

I - SUPPLY MODELLING : COST, TARIFF RATES AND ENERGY CONSUMPTION MODELS

Supply modelling, in the context of freight transportation, involves mainly models aimed at quantifying carrier transportation attributes such as carrier and terminal operating costs, freight tariff rates, and carrier energy consumption rates.

Freight tariff rates models are relatively rare in the literature. This is mainly due to the great difficulty of modelling the complex structure of motivations behind the tariff setting process. Tariff rates strongly depend on the attributes of the commodity and on the attributes of the carrier, on the specific origin-destination pair and on the route chosen. In addition, tariff rate structures often embody many exception rules, subtle applications and extra-economic criteria, such as the "fairness" concept, especially in the context of a regulated industry. The recent paper by Tye and Leonard (1983) is a good example of such discussions in the context of tariff setting for the U.S. railway system.

Aggregate operating cost and energy consumption models are more abundant in the literature and we review some of the more typical models with emphazis on those which may be used in strategic planning.

Two basic methodologies have been used to estimate transport attributes :

i) the activity approach where the number of physical and operational components required to perform a service is first found; unit "costs" (operating costs, fuel consumption rates, etc.) are then assigned to these components; the total attribute value is then obtained as the combination of these individual costs (Murphy, 1976; Miller, 1970; etc.);

ii) the econometric (or accounting) approach where statistical equations relate attribute variations to variations in the values of system parameters (Kneafsey, 1975; Stenason and Bandeen, 1965, etc.)

Hybrid approaches combining these two methodologies are, however, most widely proposed and the studies reviewed herein are good examples of that tendency.

McGinnis et al. (1981) study the Multi-State Transportation Corridor, a large and mainly under-developed area in the U.S., which includes parts of eight states from Florida to Kansas. The objective is the development of analytical procedures that can quantify the interactions between programs for the improvement of the multi-modal transportation service for freight and economic development opportunities. Each link in their transportation network is mode dedicated and has three attributes : transport cost, transport time and transport time variance. The transport cost represents the cost to the carrier of providing the service and is computed by a formula which follows the work of Gill and Whitten (1976) :

$$CT_{ij}^{km} = \sum_{e} p^{emk} \sum_{g} d_{ij}^{gm} \left(K_{g}^{em} + L_{g}^{em}\right) I^{k}$$

where

CT_{ij}^{km} = total linehaul cost per ton of commodity k moving from zone i to zone j by mode m (= highway, railway, wateraway).

p^{emk} = fraction of commodity k using vehicle type e from mode m.

d_{ij}^{gm} = distance in miles of arc (i,j) in the cost area g of the carrier mode m.

K_{g}^{em} = fixed linehaul cost (not varying with volume charges) per ton-mile in cost area g, for carrier mode m, vehicle type e.

L_g^{em} = variable linehaul cost per ton-mile in cost area g, for carrier mode m, vehicle type e.

I^k = density multiplier for commodity k.

Similar formulae are used to compute the "transport" cost through terminals :

$$CL_i^{km} = \sum_e p^{emk} \; r^{emk} \; RT_{gi}^{em} \; I^k$$

$$CU_i^{km} = \sum_e p^{emk} \; (1-r^{emk}) \; RT_{gi}^{em} \; I^k$$

where

CL_i^{km} = loading cost per ton for commodity k at a terminal of mode m, in zone i.

CU_i^{km} = unloading cost per ton for commodity k at a terminal of mode m, in zone i.

r^{emk} = fraction of terminal cost for commodity k traveling by mode m using the vehicle type e.

RT_{gi}^{em} = terminal cost per ton for any commodity traveling by mode m, using a vehicle type e in cost area g associated with zone i.

Unit costs for these models were obtained from U.S. statistical sources. Somewhat simpler formulae were used for barge transportation. No analytical formulae were developped for rail classification costs and times. Location specific figures, as reported in previous studies, were used instead.

For tariff rate modelling, these authors use the approach developed at M.I.T. by Samuelson and others (1976, 1977a, 1977b). It is a commodity abstract, mode specific, econometric type model based on 1973 data. The general form is :

$$\ell n \text{ Rate} = \alpha_1 \ell n \text{ Distance} + \alpha_2 \ell n \text{ Weight} + \alpha_3 \ell n \text{ Density} + \alpha_4 \ell n \text{ Value} + \alpha_5 L + \alpha_6 G + \alpha_7 P + \alpha_8 F + \alpha_9 T + \alpha_{10} S + \alpha_{11} H + \alpha_{12}$$

where

Distance = distance from origin to destination in miles
Weight = weight of shipment in pounds
Density = density in pounds per cubic foot
Value = value per pounds in 1972 dollars at wholesale prices.

The dummy variables indicate if the commodity is a Liquid, a Gas, or a Particulate, if Freezing or other Temperature control is required, and if Shock protection or other special Handling is required.

Daughety et al. (1979b, 1983) propose a model of the costs of railroad operations where the costs of the various inputs (engines, cars, fuel, crews, etc.) are related to the flows of traffic over the links (linehaul and yard) of the network :

$$\min G(f) = \sum_{(i,j)} c_{ij}(f_{ij}) f_{ij}$$

$$\text{s.t.} \quad \sum_j f^q_{ij} - \sum_i f^q_{ji} = z_{iq} \qquad \text{for all } i,q$$

$$f_{ij} = \sum_q f^q_{ij} \qquad \text{for all } (i,j)$$

$$f_{ij}, f^q_{ij} \geq 0 \qquad \text{for all } (i,j)$$

where

z_{iq} : volume of total demand from i to q

f^q_{ij} : car loads on (i,j) to destination q

f_{ij} : total car loads on (i,j)

$c_{ij}(f_{ij})$: unit cost of flow on (i,j)

These unit costs include the costs of all the inputs required to cross a particular link. For a linehaul link these inputs are the costs of : train crews, fuel, locomotive ownership and maintenance, car-hire, ownership and maintenance and track maintenance. For example :

. wage costs per carload

$$c_{1ij}(f_{ij}) = p_w \frac{(1+E)M_{ij}}{ATL}$$

. fuel costs per car load

$$c_{2ij}(f_{ij}) = p_F \, r_1 \, M_{ij}$$

where

p_w : train crew wage costs per train-mile

E : empty-to-loaded car-mile ratio

ATL : average train length (cars)

M_{ij} : length of (i,j)

p_f : price of fuel per gallon

r_1 : fuel consumption rate per loaded car-mile

The unit costs and the constants making-up these formulae and the yard operating cost formula were derived from historical data.

For links representing yard operations, the yard operating cost per engine-hour is computed as :

$$\frac{p_y}{Y} + p_F \, r_2 + p_v$$

where

p_y = price of a yard engine

γ = utilization level (hours/engine/month) of yard engines

r_2 = fuel consumption rate per engine-hour

p_y = yard wage rate per engine-hour

while the number of engine-hours is related to the number of cars handled through regression models which are calibrated for each yard.

A method of successive linear approximations of the objective function, following the algorithm of LeBlanc et al. (1975), is used to solve the problem.

A similar approach is also proposed by Petersen and Tulett (1980). Line and yard submodels developped by Petersen (see section V), as well as a train performance calculator developed by the World Bank are first used to compute the characteristics of the operation of the system. The total operating cost is then the sum of the operating costs for each line and yard in the system. First order costing relationships are used, based on data from a major Canadian railway. Among the major factors which determine operating costs, the authors retained line costs (rail and ties capital costs, depreciation and maintenance costs), fuel and labour costs, car and engine capital costs, depreciation and maintenance costs, etc.

To calculate energy consumption (as well as other train performance characteristics), Petersen and Tulett used models developed by the World Bank based on the Harvard Model. Thus, the fuel required to operate the train over the line is given by :

$$FUEL = FRATE \cdot HP \cdot N \{(0,15+0,85\ V/V_{MAX})\ R + 0,15\ (W-R+0,25LDELAY)\}$$

where

FUEL : consumption in gallons

FRATE : fuel consumption in gallons/horsepower-hour

HP : horsepower per locomotive

N : number of locomotives

V : speed in mph

V_{MAX} : maximum continuous speed permissible on that line with that type of train

R : d/V, the free running time in hours

d : line length in miles

LDELAY : locomotive delay per trip.

W : expected transit time.

The "Transportation Energy Conservation Model" (TEC 1978) uses simulation to compute the total energy consumption for each technology, (gasoline or diesel trucks, diesel or electric locomotives, etc.) for each transportation mode. Based on historical U.S. data (time series of rail engine horsepower distribution, truck size distribution, truck acquisition and scrapage, and so on; also average consumption rates, carrier characteristics, etc.), the model simulates, for each mode, the evolution of the park of vehicles and its utilization in the inter-city freight transportation (the trip length being the discriminant factor). Using unit consumption rates, the total energy consumption is then computed.

Finally, nonlinear regression models were used by Zaniewski et al. (1979) to determine the effects of the road conditions and vehicle type upon the fuel consumption of different vehicles rolling upon Brazilian roads.

The general form of the model is :

$$FUEL = a_0 \exp (a_1 x_1 + a_2 x_2 + \ldots).$$

Here are two examples of the final models (seven types of vehicles were studied) :

$$FUEL(CAR) = a_0 \exp \{a_1 S + a_2(S)\, GR + a_3 P(GR + C_1) + a_4(C_2 - GE) + a_5 QI(GR + C_3)\}$$

$$FUEL(MEDIUM\ TRUCK) = b_0 \exp \{(a_6 + a_7 P(GR + C_4))\, S + (a_8 P + a_9 GR)(C_5 - GE) + a_{10} QI\}$$

where

$a_0, b_0, a_1, \ldots, a_{10}$	: estimated parameters
$C_1, \ldots, C_5$	: constants
S	: speed
GR	: grade of road in %
P	: weight (metric tons) of vehicle
GE	: gear of vehicle
QI	: roughness of road
Exp	: the exponential function.

The main conclusion of this section is that developing and calibrating adequate models for the supply side of a freight transportation network is a critical, complex and difficult operation.

Energy consumption models seem to be the easiest (relatively speaking) to develop, provided sufficient data is available. Then, certain factors seem to influence energy consumption more than others and these should be integrated into the model : the technology of the mode, the type of vehicle, the characteristics of the road, the weight of the load, etc.

As mentioned at the beginning of this section, tariff models are few and relatively complex. It is our opinion however, that for strategic planning purposes, much "simpler" and differently oriented models are required. These models should reflect less of the specific characteristics of the commodites and/or modes considered and more of the "political" decisions concerning, for example, market penetration by a certain mode, or the division of a market between several modes, or preferences by a particular mode for certain commodity types, etc. This is especially true for a model reflecting the Brazilian transportation system where the rail system is state-owned and centrally planned, while trucks are, for the most part, individually owned and operated.

Modelling transportation costs also proved to be a difficult task. We found a number of quite detailed models for the costs of operating a railway : operating a number of trains on the lines, moving cars in a yard, paying crews, etc. These models do not consider commodities and are probably too disaggregated for strategic decision-making. Even so, we were not able to find comparable models for modes other than rail.

The models of McGinnis et al. (1981), on the other hand, are commodity specific and also very aggregated and defined for all modes. The biggest disadvantage of this method is the huge amount of data required and the deep understanding of each mode, commodity and operation that are necessary to define and calibrate the models. This is, however, in our opinion an approach worth exploring.

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II - DEMAND MODELLING

Freight demand modelling : spatial distribution within an input-output framework

Some of the first inter-regional freight flow models which took into account the economic activities of the region were simply spatial disaggregation variances of the national Leontief input-output economic model. For example, in Isard's (1951) model the basic structural equations are as follows :

$$z_i^k - \sum_h \sum_j x_{ij}^{kh} = \sum_j y_{ij}^k \qquad \text{for all } k,h,$$

$$x_{ij}^{kh} = b_{ij}^{kh} z_j^h \qquad \text{for all } h,k,i,j$$

where z_i^k is the total output of industry in k region i, x_{ij}^{kh} is the transaction flow for industry k in region i to industry h in region j, while y_{ij}^k represents the part of the final-demand sector for the commodity k in region j fulfilled by the output of region i. Finally, b_{ij}^{kh} is the spatial input-output coefficient. Note the assumption of a one-to-one correspondance between productive sectors and goods or services.

The collection of data for interindustry, interregional flows for the estimation of the spatial input-output coefficients (b_{ij}^{kh}) by direct observation or even by sampling freight movements, is definitely prohibitive. Consequently, some approximation method which may involve rather stringent assumptions must be resorted to. For example, Moses (1955) and Chenery et al. (1953) assumed a constant ratio between the quantity of a certain commodity which is imported from another region and the quantity provided internally for production to calculate spatial

trade coefficients[1]. This stability of the inter-regional trade structure, embedded in the Moses-Chenery type models, implies the insensitivity of trade flows to modifications in the transportation system or the tariff structure.

A rather elegant method for dealing with this problem was suggested by Leontieff-Strout (1963). It overcomes the rigidity of the trade coefficients by assuming that the ultimate destination and origin of the goods are irrelevant to producers and consumers who respond only to prices. They further suggest that inter-regional trade flows have a gravity functional form. Wilson (1970) later showed that Leontieff-Strout's model is an instance of the following more general entropy model :

$$\text{Min} \sum_{ijk} x_{ij}^k \, \ell n \, x_{ij}^k$$

subject to

$$\sum_j x_{ji}^k - \sum_k a_i^{kh} \cdot \sum_j x_{ij}^k = y_i^k \qquad \text{for all } k,i$$

$$\sum_{ij} c_{ij}^k \, x_{ij}^k = c^k \qquad \text{for all } k$$

where

x_{ij}^k is the trade flow of commodity k between i and j,

a_i^{kh} is the regional technical input-output coefficient

c_{ij}^k is a measure of the transport cost for shipping one unit of commodity k from i to j

y_i^k is the final demand of commodity k at i.

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[1] The spatial input-output coefficient b_{ij}^{kh} is commonly defined as the product of a technical and a trade coefficient.

Following the Leontief-Strout and Wilson approach, Los (1980) formulated a minimum information inter-regional freight flow model for Canada. This model used a rectangular input-output coefficient matrix and the following objective function :

$$\underset{(x_{ij}^k)}{\text{Max}} \; \{\gamma \sum_{ijk} s_{ij}^k x_{ij}^k - \sum_{ijk} x_{ij}^k \ln (x_{ij}^k / v_{ij}^k)\}$$

where s_{ij}^k is a measure of the profit obtained in producing one dollar of output in region j, v_{ij}^k is an a priori observed flow and γ is a calibration parameter. The second term of the objective function is the Kullback-Liebler (1965) "discriminatory information function" used mainly in the analysis of contingency tables in statistics, and introduced into transportation modelling by Snickars and Weibull (1977). In Los' model, this information term is used to model the inertia effect in transport and economic systems.

To overcome a calibration problem encountered in the application of Los' model to the Canadian Provinces, Bigras et al. (1983) proposed the use of the following objective function :

$$\text{Min} \sum_{ijk} x_{ij}^k \ln (x_{ij}^k / w_{ij}^k)$$

where

$$w_{ij}^k = f(c_{ij}^k, E, \gamma)$$

and c_{ij}^k is a measure of the transportation cost, E is a vector of explanatory variables and γ a vector of parameters. The calibration of w_{ij}^k is achieved using regression techniques and the a priori flows (v_{ij}^k).

Embedding an input-output framework within an inter-regional freight flow model to stress the interrelationship between economic activities and freight transport demands is a theoretically attractive and satisfying modelling approach. However, theoretical attractiveness must quite often be tempered by the practical availability of data. This limitation in supply of data leads to the frequent use of simpler models of the spatial distribution of freight flows, such as the standard Hitchcock transportation linear programming model (O'Sullivan and Ralston, 1974; Henderson, 1958; Land, 1957; Heady and Skold, 1966) or Wilson's standard maximum entropy model (Black, 1971, 1972; Metra, 1971; Chisholm and O'Sullivan, 1973, Pitfield, 1978).

Freight transportation demand derived from spatial price equilibrium models

A spatial price equilibrium for a given product is established when : (i) the demand price in the market equals the delivered price (supply price and transportation cost) of the commodity for all positive inter-regional flows; and (ii) if the demand price is greater than the delivered price no shipment may occur. This state of equilibrium may be expressed as follows :

$$\pi_i^k + c_{ij}^k > p_j^k$$

$$= p_j^k \quad \text{if} \quad x_{ij}^k \quad \text{is greater than 0}$$

$$\sum_j x_{ij}^k = O_i^k \qquad \text{for all } i,k$$

$$\sum_i x_{ij}^k = d_j^k \qquad \text{for all } i,k$$

$$x_{ij}^k > 0 \qquad \text{for all } i,j,k$$

$$\pi_i^k = S_i^k(O_i) \qquad \text{for all } i,k$$

$$d_j^k = D_j^k(p_j) \qquad \text{for all } j,k$$

where

O_i^k = amount of commodity k produced at i

d_j^k = amount of commodity k demanded at j

x_{ij}^k = inter-regional flow commodity k

π_i^k = the unit price of supplying the quantity of O_i^k

$S_i^k(O_i)$ = supply function; $O_i = (O_i^k)$

p_j^k = demand price of commodity k

$D_j^k(p_j)$ = demand function; $p_j = (p_j^k)$

C_{ij}^k = transportation cost of commodity k from i to j

This equilibrium model is a multi-commodity version of Samuelson's (1952) original single commodity model. Note that the origin-destination freight transportation demands are not directly articulated in this model, but they are rather obtained as a by-product of any price equilibrium solution.

Takayama and Judge (1964, 1971) using linear supply and demand functions were apparently the first to propose an equivalent quadratic programming formulation to the above equilibrium conditions. Since then, several empirical applications of the quadratic programming model have been made. For example Schmitz and Bawden (1973) study the international trade of wheat. The impact of changes in rail freight tariff rates on Canadian wheat exports is studied by Nagy et al. (1980).

More recently, McKinnon (1975, 1976) studied the price equilibrium model within a fixed-point framework; Hazell and Scandizzo (1974, 1977) introduced an interesting stochastic supply model for a single region, and Florian and Los (1981) considered non-linear transportation

costs and formulated the single product model as a convex program and the multicommodity model as a variational inequality problem. This line of approach is also followed by Tobin and Friesz (1983). Finally, Thore (1982) introduced an income measure into the price equilibrium model to deal with the case where the national economy is dominated by one or several products.

Freight abstract-mode demand modelling

As part of the Northeast Corridor Transportation Project (U.S.-A.), Mathematica (1967) introduced Quantd and Beaumol's abstract-mode model used in passenger transport demand, into freight demand modelling. The abstract mode approach is built upon the postulate that the traveller's choice of mode (shipper's choice in the freight transportation context) depends on the mode's service and performance attributes. The mode per se has no special significance to its users other than as the collection of attributes it possesses. Quantd and Beaumol's model consists of two components : generation-distribution and mode-split. The generation-distribution component has a gravity functional form and is a function of origin and destination socioeconomic variables (populations, incomes, industrial character indices) and impedance factors (travel time by the least time mode, cost by the least cost mode, departure frequency by the most frequent mode). The mode-split component has a multiplicative form also and is a function of the number of modes available and the relative performance attributed with respect to the best mode.

The form used in Mathematica's study is :

$$x_{ijm} = a_0 P_i^{a_1} P_j^{a_2} y_i^{a_3} y_j^{a_4} M_i^{a_5} M_j^{a_6} N_{ij}^{a_7} (T^b_{ij})^{b_0} (T^r_{ijm})^{b_1} (c^b_{ij})^{b_0} (c^r_{ijm})^{d_1}$$

where :

x_{ijm} = volume of freight flow from i to j by mode m

P_i, P_j = populations

y_i, y_j = gross regional products

M_i, M_j = industrial character indices such as percent of labor force employed in mining and manufacturing

T^b_{ij} = shipping time from i to j by the least time mode

T^r_{ijm} = shipping time by mode m divided by the least time

C^b_{ij} = least cost of shipping from i to j

C^r_{ijm} = cost of mode m divided by that least cost

N_{ij} = number of modes serving i and j

Level of service and market attributes as well as policy variables may be added in a straightforward manner. To avoid to calibrate a separate model for each commodity being studied, and also to remove ambiguity in defining the best mode, it is advisable to consider adding commodity attributes as well as a shipment size variable. Some preliminary tests involving the mode-split component have been carried out by Herendeen (1969) with mixed results.

Another abstract-mode freight demand model was proposed by Mathematica (1967). This model was constructed by combining classical inventory theory with the abstract-mode concept. The derivation of the model follows Baumol's (1970) approach. First, the total annual transportation cost of an industry in location j receiving commodity k from location i

by mode m is expressed as the sum of direct shipping costs, total in-transit carrying costs and safety inventory costs. The marginal cost is then set equal to marginal revenue. Under appropriate assumptions concerning the cost functions and after some approximations, the following model was obtained :

$$x^k_{ijm} = a_0 + a_1(\Delta p^k_{ij}) + a_2\, C^k_{ijm} + a_3(S^k_j\, T^k_{ijm}) + a_4(S^k_j + T^k_{ijm})^{\frac{1}{2}}$$

where :

x^k_{ijm} = flow of commodity k from i to j by mode m

Δp^k_{ij} = the difference in the value of commodity k between locations i and j

C^k_{ijm} = shipping cost per unit of commodity k from i to j using mode m

S^k_j = time between shipments of commodity k to j

T^t_{ijm} = average shipping time of commodity k from i to j using mode m

It may not be obvious from the above functional form, but the model implicitly requires a great variety of microeconomic data such as the value of the commodity, the sales rate of the commodity, holding cost, shortage cost, interest rate on capital, ordering cost, etc. It is also not clear how the above model for an individual shipper should be aggregated to model the behaviour of all shippers in a region. These problems would be a major obstacle in the practical implementation of this methodological approach.

An attempt to operationalize the concept of an abstract freight mode may be found in Roberts (1970). The author developped a procedure to compute a so-called "commodity preference" vector, which essentially quantifies the shipper's imputed service costs and performance attributes such as travel time, waiting time, variability of travel time and

the probability of loss and damage. Preliminary results were obtained for two aggregate commodity groups.

Freight demand models derived from a neoclassical production theoretic approach

Recognizing that transportation is a productive input and should be treated analytically like any other input, it is advocated in this approach that freight demand should be derived from the firm's underlying production or cost functions.

There are two related methods for deriving such freight demand models. One method would involve first postulating and calibrating a firm production functional form satisfying certain regularity conditions and then solving a production constrained cost minimization mathematical program for freight demands. No application of this approach has been found. Another method, which avoids the difficult task of calibrating a production function, would consist of specifying a differentiable functional form for the firm's cost function, also satisfying certain regularity conditions and obtain the derived demands by differentiating the cost function with respect to transportation prices (Shephard, 1953). The demand models used in Sloss (1971), Perle (1964) and more recently, Oum (1977, 1978), Friedlander and Spady (1980) follow this second approach.

The general functional form of the demand model derived from the firm's cost function according to a result established earlier by Shephard (1953), is :

$$x^{k}_{ijm} = \partial C(Y,I,P_L P_T)/\partial P_{ijm}$$

where :

x^k_{ijm} = flow of commodity k on link ij by mode m

Y = firm's vector of total output to be shipped to various markets

I = vector of fixed inputs (capital, material)

P_L = vector of prices of input other than transportation service (labour)

P_T = (P^k_{ijm}) ; P^k_{ijm} = price of transportation service for commodity k on link ij by mode m.

Using time-series data for Canada, Sloss (1971) calibrated a highly aggregated intercity freight demand model for the hired truck mode. Perle (1964) conducted one of the first major studies in freight transportation ; he estimated demand functions for the rail and truck modes using time-series and cross-sectional U.S. data. Separated functions were estimated for distinct commodity groups and differences between spatially separated regions were considered by adding dummy variables. Oum (1977, 1978) and Friedlaender and Spady (1980) assumed that the firm's cost function can be expressed by a "translog" approximation which allows the free variation of price elasticities and elasticities of substitution (see Christensen et al., (1973) for a discussion of the translog cost function).

Friedlaender and Spady's price function has the following general functional form :

$$P^k_{ijm} = r_m + f(q_{1m}, q_{2m}, q_{3m}, q_{4m})$$

where :

r_m = rate of mode m

q_{1m} = value of the commodity carried by mode m

q_{2m} = density of the commodity carried by mode m

q_{3m} = average length of haul of the commodity carried by mode m

q_{4m} = average shipment size of the commodity carried by mode m

The function $f(q_m)$ is intended to take into account inventory costs incurred by goods-in-transit.

Using a combination of cross-sectional and time-series data for eight aggregate commodity groups and five broad U.S. geographic regions, Friedlander and Spady estimated the derived demand share for truck and rail services. The results are encouraging but inconclusive due to limitations in the data used. Also, the resulting models cannot be used to assess the sensitivity of the demand to variation in the performance attributes.

This latter issue is resolved in Oum (1978)'s models. Instead of conditioning the commodity attributes to reflect inventory costs, Oum chose to include explicitly either the quality attributes of the mode or the perceived values of these attributes in the transportation price functions. The quality attributes of the mode considered are the average transit time and the standard deviation of the transit time distribution. These values are estimated by regression techniques for two broad commodity groups only : bulk and non-bulk. Extensive numerical testing has been carried out by Oum (1978) using aggregate cross-sectional data for the hired truck and rail modes in Canada. Again, the results obtained are inconclusive due to imperfections in the data used and the complete absence of private truck mode data. Nevertheless, Oum's work represents the state of the art concerning derived demand methodology.

Mode choice modelling

Among the large variety of mode-choice models which have been proposed in the literature, two distinct approaches have emerged : empirical descriptive modelling and probabilistic modelling.

In the descriptive modelling approach, the emphasis is on the identification of critical determinants of mode choice. The following factors are the most frequently used :

commodity attributes - type, value, bulkiness, density, shelf life
shipment attributes - size and distance from destination
shipper attributes - frequency, location, size of firm
mode attributes - tariff rates, transit time, variation in transit time, punctuality, reliability, frequency.

Among the numerous studies, Church (1967, 1971) investigated the impact of shipment size and distance from destination on the truck share of the market, while Buhl (1969) considered the size of the firm and the type of the commodity shipped. Studies by Evans and Southard (1974), Stock and Lalonde (1978) and McGinnis (1980) are representative of more recent work.

The second group of models based on a probabilistic analysis is theoretically attractive and more satisfying. Discriminant and logit analysis are most frequently proposed for estimating conditional mode choice probabilities using both aggregated and disaggregated data. Probit models, which exhibit certain computational difficulties, are less frequently used.

Discriminant analysis, which is commonly used in biology to classify a population into two subpopulations with minimum error using a linear discriminant function, has been used by Miklius (1969), Antle and Haynes (1971), Bayliss (1973) and Hardwig and Linton (1974) in the freight mode-choice area.

Kullman (1973) estimated a binomial logit model with aggregated data to predict the truck-rail modal-choice as a function of level of service attributes, commodity attributes and market attributes. Hartwig and Linton (1974) also compared the logit, probit and discriminant functions in modelling the shipper's mode-choice between truck and rail. In their models, they used the difference between truck and rail transit times, the difference between truck and rail charges, the difference in standard deviations of the transit time distributions and the value of the commodity as independent variables. Finally, Terziev et al. (1975) in a non-empirical technical report, described a detailed list of shipment, commodity, mode level of service and market attributes which might be determinant factors in mode choice, and subsequently recommended the use of a disaggregate multinomial logit model.

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III - DISTRIBUTION MODELS

We review, in this section, models which address the strategic planning issue of deciding where intermediate distribution centers should be located, what sizes they should be and how commodities should be routed from sources of production through the distribution centers and on to customers. In this, we closely follow the classification and notation of the literature review to be found in Aikens (1982). The interested reader should refer to this work for more details, especially concerning the solution methods mentioned here. The associated tactical planning issues concerning routing and scheduling of vehicles and crews is not considered here. A detailed review of these subjects may be found in Bodin et al. (1983).

Models for distribution-location problems may be broadly classified according to :

- whether or not capacities are specified for some (or all) elements of the distribution network ;
- the number of echelons (zero, single, multiple) of transshipment points between supply and demand nodes;
- the number of commodities;
- the form of the cost functions (linear or not);
- whether the planning horizon is static or dynamic.

The simplest location model (single commodity, uncapacitated, zero-echelon, linear costs) is the Uncapacitated Simple Facility Location Model (UFL) :

$$\text{Minimize} \quad \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i z_i$$

$$\text{Subject to} \quad \sum_{i \in I} x_{ij} = 1 \qquad j \in J$$

$$x_{ij} \leq z_i \qquad i \in I, j \in J$$

$$x_{ij} \geq 0 \qquad i \in I, j \in J$$

$$z_i \in \{0,1\}$$

where :

x_{ij} : proportion of demand of customer j satisfied by facility i

$$z_i = \begin{cases} 1 & \text{if facility i is established} \\ 0 & \text{otherwise} \end{cases}$$

c_{ij} : total production and distribution cost to supply customer j by facility i

f_i : fixed cost of establishing facility i

I : set of candidate facility sites

J : set of customer zones.

Branch-and-bound solution techniques have most frequently been proposed for this problem : Efroymson and Ray (1966) were the first to propose such a method, while Spielberg (1969) used an implicit enumeration technique. Khumawala (1972) compared various branching rules. Gizelis and Samoulidis (1980), Khumawala and Whybark (1976, a dynamic version of the model) and others also used branch-and-bound algorithms for simple location formulations. Erlenkotter (1978) has reported very impressive computational results (less than 5 sec. on an IBM 360/91 for a 200 plant, 200 customer problem) using a multiplier adjustment method in which the dual of the problem is reduced to a form involving only the multipliers of the first set of constraints which are then adjusted incrementally in such a way that complementary slackness violations are reduced. Morris (1978) Negelhout and Thompson (1981) and Laporte and Nobert (1981) have also worked on the single facility location problem.

Kaufman et al. (1977) proposed a slightly more general single-echelon, two-level distribution model, requiring the simultaneous location of plants and distribution centers :

$$\text{Minimize} \quad : \sum_{i\in I}\sum_{j\in J}\sum_{k\in K} c_{ijk}\, x_{ijk} + \sum_{i\in I} f_i + \sum_{j\in J} g_j\, y_j$$

$$\text{subject to} : \sum_{i\in i}\sum_{j\in j} x_{ijk} = 1 \qquad k\in k$$

$$\sum_{j\in J} x_{ijk} \leq z_i \qquad i\in I, k\in K$$

$$\sum_{i\in I} x_{ijk} \leq y_j \qquad j\in j, k\in K$$

$$z_i \leq y_i \qquad i\in I$$

$$x_{ijk} \geq 0 \qquad i\in I, j\in j, k\in k$$

$$y_j, z_i \in \{0,1\} \qquad i\in i, j\in J$$

where i,j,k are indices for plants, warehouses and customers respectively. The problem was solved by a branch-and-bound technique, generalizing the work of Efroymson and Ray (1966).

A generalization of (UFL) in which commodities are differentiated as well, is called the Multicommodity Uncapacitated Facility Location Model (MUF) :

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J}\sum_{p\in P} c_{ijp}\, x_{ijp} + \sum_{i\in I}\sum_{p\in P} f_{ip}\, z_{ip}$$

$$\text{subject to} \sum_{i\in I} x_{ijp} = 1 \text{ if } D_{jp} \bullet GT \bullet 0 \qquad j\in J, p\in P$$

$$\sum_{p\in P} z_{ip} \leq 1 \qquad i\in I$$

$$\sum_{j\in J} x_{ijp} \leq \sum_{j\in J} z_{ip} \qquad i\in I, p\in P$$

$$x_{ijp} \geq 0 \qquad i\in I, j\in J, p\in P$$

$$z_{ip} \in \{0,1\} \qquad i\in I, p\in P$$

where p, i, j are indices for commodities, plants and customers respectively, and each facility is restricted to one commodity only (and "•GT•" stands for "greater than"). Warszawski (1973) has proposed a heuristic solution method, while Karkazis and Boffey (1981) have developed two more efficient, dual-based approaches and Neebe and Khumawala (1981) have suggested an efficient branch-and-bound algorithm for solving this problem.

Warszawski (1977) also examined a dynamic version of (UFL) in which the locations of the supply nodes may change over time :

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J}\sum_{s\in S} c_{ijs}\, x_{ijs} + \sum_{i\in I}\sum_{s\subset S} b_{is}\, z_{is} + \sum_{i\in I} a_{i1} z_{i1} + \sum_{i\in I}\sum_{s\in S'} a_{is}\, z_{is}\,(1-z_{i,s-1})$$

$$\text{subject to} \quad \sum_{i\in I} x_{ijs} = 1 \quad \text{if} \quad D_{is} \bullet GT \bullet 0 \qquad j\in J, s\in S$$

$$\sum_{j\in J} x_{iks} \leq \sum_{j\in J} z_{ij} \qquad i\in I, s\in S$$

$$x_{ijsl} \geq 0 \qquad i\in I, j\in J, s\in S$$

$$z_{is} \in \{0,1\} \qquad i\in I, s\in S$$

where :

a_{is} = set-up cost of establishing a supply source at location i in stage s (incurred only if the source is relocated from stage s-1 to stage s)

b_{is} = fixed set-up cost of establishing a supply source at location i

S = set of stages s; $S' = S - \{1\}$.

This Simple Multistage Plant Location Model was inspired by a large construction project, where the sites of some important processing activities could change as the requirements for various materials varied during the stages of construction. Two solution methods have been tested for this model : an approximate dynamic programming recursion and a procedure based on highest marginal savings. The latter method was computationnally more efficient.

The Capacitated Facility Location Model (CFL) may take the following form :

$$\text{Minimize} \quad \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i z_i$$

$$\text{subject to} \quad \sum_{j \in J} x_{ij} \leq s_i z_i \qquad i \in I$$

$$\sum_{i \in I} x_{ij} = D_j \qquad j \in J$$

$$x_{ij} \geq 0 \qquad i \in I, j \in J$$

$$z_i \in \{0,1\} \qquad i \in I$$

where :

x_{ij} : amount of flow from facility i to customer j

c_{ij} : the associated unit cost

D_j : demand of customer j

s_i : capacity of distribution center i

Akinc and Khumawala (1977) proposed a branch-and-bound solution technique and have studied two node selection criteria and a number of bounding rules which generalize those examined by Khumawala (1972) for the (UFL) Model. Nauss (1978) has also proposed a branch-and-bound algorithm which appears to be computationally more efficient. Nauss used tight lower bounds and penalties derived from the Lagrangian relaxation of the problem (solved by decomposition techniques).

Lagrangian relaxation has also been applied by Geoffrion and McBride (1978) to a generalized version of this model where lower as well as upper bounds were imposed on the flow variables and linear side constraints were allowed.

The formulation (where the flow variables x again represent proportions) of this Generalized Capacitated Facility Location Model (GCFL) is :

$$\text{Minimize} \quad \sum_{i \in I} \sum_{j \in J} c_{ij} x_{ij} + \sum_{i \in I} f_i z_i$$

$$\text{subject to} \quad \underline{V}_i z_i \leq \sum_{j \in J} D_j x_{ij} \leq \overline{V}_i z_i \qquad i \in I$$

$$\sum_{j \in J} a_{ij} x_{ij} + \sum_{j \in J} b_{ij} z_{ij} = r_i \qquad i \in I,$$

$$\sum_{i \in I} x_{ij} = D_j \qquad j \in J$$

$$0 \leq x_{ij} \leq 1 \qquad i \in I, j \in J$$

$$z_i \in \{0,1\} \qquad i \in I$$

In the same paper, Geoffrion and McBride compared the performances of the branch-and-bound algorithm when different techniques for the computation of lower bounds are used. Significantly better results (approximately five times faster on a typical problem with 24 facilities, 102 customers, 298 links and 76 linear constraints) are reported when Lagrangian relaxation is used instead of a linear programming relaxation completed by a penalty technique.

Balachandran and Jain (1976) used branch-and-bound techniques and LeBlanc (1977) used heuristic methods to deal with the single-commodity version of the problem, where demands are random variables. This

Stochastic Transportation Location Problem (STLP) may be formulated as :

$$\text{Minimize} \quad \sum_{i\in I^*} \sum_{j\in J} c_{ij}\, x_{ij} +$$

$$+ \sum_{j\in J} \left[\int_0^{y_j} (y_j - v)\phi_j(v)dv + p_j \int_{y_j}^{\infty} (v - y_j)\phi_j(v)dv\right]$$

$$+ \sum_{i\in I} f_i\, z_i$$

$$\text{subject to} \quad y_j = \sum_{i\in I} x_{ij} \qquad j\in J$$

$$\sum_{j\in J} x_{ij} \leq S_i \qquad i\in I^*$$

$$x_{ij} \geq 0 \qquad j\in J, i\in I$$

$$z_i \in \{0,1\} \qquad i\in I'$$

$$z_i = 1 \qquad i\in I$$

$$y_j \geq 0 \qquad j\in J$$

where

$\phi_j(v)$: the density function for the demand for customer j

h_j : unit holding cost at location j

p_j : unit shortage cost at location j

y_j : total amount shipped into j from all supply nodes

I : set of existing supply nodes

I' : set of proposed supply nodes

I* : IUI'

Geoffrion and Graves (1974), in their now classical paper, were the first to solve the multi-commodity location problem which simultaneously deals with location, commodity flows and customer assignment, while permitting commodities to pass through an intermediate distribution center on the route from plants to customers. Geoffrion, Graves and

Lee (1978, 1979) further refined the model. The revised version imposes sole-sourcing only on a "bundle" of similar items, while the rest of the demand may be satisfied from multiple sources. Violations of upper and lower limits of the capacity of the distribution center are allowed at a penalty cost. Plant capacity is limited by upper and lower bounds, to provide some control over economies of scale. The distribution center throughputs are computed as weighted sums of the individual flows passing through. Weights and costs vary according to commodity, customer, distribution center and plant. This revised Multicommodity Single-Echelon Distribution System Model (MDSR) has the following formulation :

$$\text{Minimize} \quad \sum_{i\in I}\sum_{j\in J}\sum_{k\in K}\sum_{p\in P} c_{ijkp}\, x_{ijkp}$$

$$+ \sum_{j\in J}\Big[f_j\, z_j + \sum_{k\in K}\sum_{b\in B_k}\sum_{p\in P_k(b)} v_{jp}\,\beta_p\, D_{kp}\, y_{jkb}\Big]$$

$$+ \sum_{j\in J}\big[\underline{p}_j \underline{\nu}_j + \overline{p}_j \overline{\nu}_j\big]$$

subject to

$$\underline{S}_{ip} \le \sum_{j\in J}\sum_{k\in K} x_{jkp} \le \overline{S}_{ip} \qquad p\in P, i\in I$$

$$\sum_{i\in I} x_{ijkp} = D_{kp}\, y_{jkb} \qquad j\in J, b\in B_k, p\in P_k(b)$$

$$\sum_{j\in J} y_{jkb} = 1 \qquad k\in K, b\in B_k$$

$$\underline{V}_j\, z_j - \underline{\nu}_j \le \sum_{k\in K}\sum_{b\in B_k}\sum_{p\in P_k(b)} \beta_p D_{kp} y_{jkb} \le \overline{V}_j\, z_j + \overline{\nu}_j \qquad j\in J$$

$$x_{ijkp} \ge 0 \qquad i\in I, j\in J, k\in K, p\in P$$

$$\underline{\nu}_j,\ \overline{\nu}_j \ge 0 \qquad j\in J$$

$$y_{jk},\ z_j \in \{0,1\} \qquad j\in J, k\in K$$

where

p,i,j,k : indices for commodities, plants, distribution centers and customers respectively

v_{jp} : unit cost for commodity p at a distribution center located at j

B_k : the set of bundle indices for customer k

$P_k(b)$: the set of commodity indices corresponding to bundle b for customer k

β_p : weight for commodity p used in calculating the throughput of the distribution center

$\underline{P}_j, \overline{P}_j$: penalty rates for violating lower (upper) bounds on the flow passing through distribution center j

$\underline{S}_{ip}, \overline{S}_{ip}$: lower (upper) limit on plant capacity at location i

$\underline{V}_j, \overline{V}_j$: lower (upper) limit on distribution center capacity at location j

$\underline{v}_j, \overline{v}_j$: underflow (overflow) at distribution center j

D_{kp} : demand for product p for customer k

$$y_{jkb} = \begin{cases} 1 \text{ if the commodities in bundle b for customer k are assigned to distribution center j} \\ 0 \text{ otherwise} \end{cases}$$

The solution method employed is based on Benders decomposition and the work of Geoffrion et al. constitutes, to our knowledge, one of the few successful applications of Benders decomposition to practical problems.

Finally, note that the model and the solution algorithm have benefitted from many man-years of effort and numerous applications and that they are embedded into a complete user oriented management support system known as ODS.

Recently, Aikens (1982) took a step further, by modelling a system in which transactions were allowed to occur between any two distributions centers and by investigating the incorporation of nonlinear cost functions for the operation of the distribution centers. This Multicommodity Multi-Echelon Distribution System Model (MDM) may be written as follows :

$$\text{Minimize} \quad \sum_{p\in P} \sum_{(i,j)\in A} c_{ijp}\, x_{ijp} + \sum_{k\in I} [f_k z_k + v_k(\phi_k)]$$

$$\text{subject to} \quad \phi_k = \sum_{p\in P} x_{kp} \qquad k\in I$$

$$\underline{S}_{ip} \leq \sum_{j\in N} x_{ijp} \leq \overline{S}_{ip} \qquad i\in F, p\in P$$

$$\sum_{j\in N} x_{jip} = D_{ip} \qquad i\in C, p\in P$$

$$\underline{V}_k z_k \leq \phi_k \leq \overline{V}_j z_k \qquad k\in I$$

$$x_{ijp} \geq 0 \qquad (i,j)\in A, p\in P$$

$$x_{kp} \geq 0 \qquad k\in I, p\in P$$

$$z_k \in \{0,1\} \qquad k\in I$$

where

- N : set of nodes
- F : set of sources (plants), subset of N
- C : set of sinks (customers), subset of N
- I : set of candidate trans-shipment nodes (distribution centers)
- A : set of arcs
- P : set of commodities
- c_{ijp} : unit cost of sending flow of commodity p on arc (i,j)
- f_k : fixed set-up cost for distribution center k
- $v_k(\phi_k)$: variable cost function of the total throughpout ϕ_k for distribution center k

x_{ijp} : flow of commodity p shipped from node i to node j

x_{kp} : flow of commodity p passing through distribution center k

$$z_k = \begin{cases} 1 & \text{if distribution center k is opened} \\ 0 & \text{otherwise} \end{cases}$$

$\overline{S}_{ip}, \underline{S}_{ip}$: upper (lower) bound on supply of commodity p at source $i \in F$

D_{ip} : demand for commodity p at sink $i \in C$

$\overline{V}_k, \underline{V}_k$: upper (lower) bound on capacity at distribution center $k \in I$

When the cost functions for the distribution centers are linear, the problem is a Fixed Charge Multicommodity Flow Problem and branch-and-bound and Benders decomposition methods are investigated for its resolution. Finally a branch-and-bound algorithm (called MEDOS) is proposed, in which a new hybrid price-directive/resource-directive scheme is used together with subgradient optimization to solve the multicommodity capacitated transshipment subproblems and Lagrangean relaxation to obtain lower bounds.

A software package, implementing MEDOS, is also described and computational results are reported on a large scale application involving the national distribution of ice cream products in Australia.

Before concluding, we present a listing of some successful applications of distribution/location models.

Geoffrion (1976) reports the results of a large scale distribution warehouse location problem for a large food manufacturer using Benders decomposition.

Kochman and McCallum (1981) solved a planning problem concerned with the optimum placement of communication cables and the routing of individual circuits between demand points so that the total discounted cost over a T-period horizon is minimized. The multiperiod capacitated distribution/location problem with side constraints was solved using MPSX and a branch-and-bound scheme.

Van Roy and Gelders (1981) report the solution of a large scale single commodity single echelon problem (capacitated and with side constraints) for a bottled products distribution firm, using a variant of Erlenkotter's (1978) dual ascent method.

Nambier et al. (1981) used a heuristic to locate processing plants and collection stations and solved the associated vehicle routing problem for the latex industry in Malaysia. Heuristics were also used in the study by Jacobsen and Madsen (1970) for locating transfer points and solving the vehicle routing problem of a large newspaper firm.

Thus, for static planning horizons and linear cost functions (including the penalties for over/under-flowing of capacities), models have been proposed, solved and applied to real situations for almost any possible location-distribution problem, from the simple uncapacitated, one commodity, zero-echelon model to the capacitated , multicommodity, multiechelon formulation. Note that capacities have been applied to supply and distribution centres, but not to transportation links.

All the formulations are mixed-integer problems and, generally speaking, branch-and-bound seems to be the most successful solution technique. As usual when using branch-and-bound algorithms, the strategies by which nodes are examined and lower bounds are computed play a

determinant role in the overall performance of the algorithm and Lagrangian relaxation seems to be a very efficient technique with respect to this criterion.

Dual-based algorithms have also been efficient on some of the simpler problems, while the successful application of Benders decomposition to the capacitated, multicommodity, single-echelon distribution problem must not be forgotten.

There are very few models addressing the issues of a dynamic planning horizon or nonlinear cost functions. In our opinion, while dynamic horizons may be less important an issue when strategic planning is concerned, the same is not true for nonlinearities in the cost functions. Nonlinear functions are better suited to representing the cost of travelling on a link or through a distribution center, especially when congestion phenomena are present. Also, capacity-related penalties are better represented by nonlinear functions. The models might also be enriched by including capacities on the links of the network. Unfortunately, nonlinearities in the objective function greatly complicate the solution of the problem. Aikens (1982) briefly analyzed some of the difficulties related to solving nonlinear distribution-location formulation. The problems are, however, still open and constitute an interesting research field.

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IV - INTERMODAL SYSTEMS AND TERMINALS

The study of intermodal systems is rapidly becoming a very important subject in freight transportation. First, an ever-increasing number of freight categories is transported using more than one mode and an integrated multimode planning is therefore required. Secondly, it is becoming more and more obvious that, in order to adequately function in today's economic environment, both shippers and carriers need to be aware of the configuration of the transportation system as a whole and of the possibilities and challenges it offers. Also, national transportation planning requires, in large part, the study of intermodal transportation systems.

There are, however, several viewpoints from which one may examine intermodal systems and we will attempt to identify them in this review.

The first conclusion to be drawn from a review of the intermodal systems literature is that most of the studies done on the subject cover the technological aspects of intermodal freight transportation : the vehicles, their characteristics, operating costs, fuel consumption, and so on. A thorough review of the existing and developing technology for freight transportation together with an anotated bibliography, may be found in Vecellio et al. (1981). Note that the emphasis is mostly placed on containerization and highway/railway concepts such as piggyback (TOFC/COFC) and the bi-modal Road Railer.

One type of intermodal system is made up of three major components : the local service, linehaul and terminals. The local service component serves regional shippers using small capacity vehicles to move freight on relatively small distances between shipper delivery/pick-up

terminals and linehaul terminals. The linehaul component uses large capacity "vehicles" (trucks, trains, ships) to carry freight over significant distances to its destination. At the destination, shipments are again the responsibility of the local service component.

It should be emphasized that the terminals are an essential part of this system, as well as of any intermodal system. Consequently, we dedicate a special part of this section to terminal models.

In a recent study, Wong et al. (1980) analyze the operations of a dedicated COFC linehaul system, which is a component of such an intermodal system. The goal was to quantify the tradeoffs and relationships between the fundamental system design parameters and various operating strategies, as they impact costs and performance. On a five node, linear corridor, three operating strategies were studied : direct service, shuttle service (a train going back and forth between two stations) and freightliner service (a train stops only if it has traffic to deliver or to pick-up). A simulation model, called LINET, was developed for this study. From the following set of system operational attributes :

- linehaul train speed
- train capacity (in maximum number of containers)
- processing time at terminals (per container)
- number of trains
- number of loading and unloading platforms per station

the simulation model provides the following performance attributes :

- number of containers delivered
- average time in the system per container

. daily cost of the system
. productivity, as the effective container speed through the system (total distance traveled/total time) divided by the daily cost.

A set of closed-form analytical formulae for these performance attributes were also derived, partially based on insights gained through the use of LINET.

A second type of intermodal model considers freight transportation on a larger regional or national scale. The local delivery/pick-up component is not considered and the focus is on the linehaul aspects of all (or at least a significant number of) modes available in the region. The intermodal system is then composed of mode-dedicated or intermodal transshipment terminals and modal of the linehaul links between them.

The models in this category find routes for traffic through the multimodal network and compute volumes, costs, modal splits etc. Consequently, these models are also sometimes called "predictive" models (note that we use this term in a larger sense than Friesz et al. (1983)). The models can further be classified according to whether they use system or user-optimal approaches to modelling shipper and/or carrier decisions. Furthermore, carriers and shippers may or may not be explicitly considered and service levels may be given or may have to be found. The models further differ by the type of functions (costs, delays, etc.) and by the modelling and algorithmic techniques they use.

All the following models are of this second type of intermodal system formulation but they are all different in one or several of these characteristics. The interested reader may also consult the recent paper by Friesz et al. (1983) which reviews some of the models presented here

and discusses problems and recent development trends in predictive intercity freight network models with emphasis on the shippers equilibrium problem.

The first significant multimodal model was the Harvard model developed and applied to the Colombian transport network (see also Section VI) by Kresge and Roberts (1971). In their network, nodes correspond to cities or regions, while links represent transportation routes (not the physical links) for each mode (highway, rail, air, water) linking the nodes. It is a multicommodity model where passengers are one of the commodities. Each link of the network has a constant, perceived unit shipping cost representing the cost of waiting and travelling, as well as the cost of any uncertainties associated with the route. Modal choices and routings are determined by a shortest path routine on the multimodal network using these costs. The specific O-D flows for each commodity are computed, in general, by linear programming (Hitchock formulation) using the same costs, or by a gravity model when highly aggregated heterogeneous commodity groups are considered. Flows are then assigned using the shortest paths computed previously. Demand and supply commodity figures are obtained from a macro-economic simulation model using input/output tables which is run for each year of the study. Note that, for the transportation model, the capacity and other carrier characteristics are exogenously determined.

As part of the National Energy Transportation Study, CACI Inc. developed a multicommodity multimodal freight network (CACI, 1980; Bronzini et al., 1974, 1980a,b). The two basic assumptions of the model are (i) freight routing results exclusively from the decision of shippers aiming at a minimum cost route and (ii) the cost of a path is a

linear combination of shipping cost, travel time and energy use. In a first version of the model, commodities are first sequentially loaded on the network, which has absolute capacities on the links. This is followed by an iterative, capacity constrained, routine which searches for equilibrium. In a more recent version, a true equilibrium assignment algorithm is used, but on a single-commodity problem only (aggregate cost functions are used). Again carrier decisions and characteristics are ignored (as in the case of the role of carrier decisions in freight routings) or poorly estimated. The results obtained on historical data were not very impressive.

Friesz et al. (1981) developed a predictive freight model called FNEM (for Freight Network Equilibrium Model), which explicitly considers shippers and carriers and includes nonlinear cost and delay functions to respond to congestion conditions on the network. FNEM is a sequential model made up of three submodels :

(i) Shipper submodel. This uses a very aggregate network representing the network shippers perceive : O-D pairs, transshipment points, routes, etc. Wardrop's first principle is used to describe the behavior of shippers. The model is an elastic transportation demand, user-optimizing trip assignment model expressed as an optimization formulation and solved by a Frank-Wolfe like algorithm.

(ii) A "bookkeeping" procedure computes carrier O-D demands from the results of the first submodel.

(iii) Carriers submodel. Carriers are assumed to sequentially react to the demands of shippers. They are also assumed to be individual operating-cost optimizing entities whose behaviour is described by Wardrop's second principle. Each carrier sub-model is a fixed-

travel demand, system-optimizing trip assignment formulation on the full network of the particular carrier. The model is in optimization form and is also solved by Frank-Wolfe-like techniques.

This model has obtained significantly better results that the previous one. It presents, however, some very serious shortcomings, principally generated by the sequential treatment of shipper/carrier relationships. We also believe that some of the assumptions in both submodels call for closer scrutiny and that, in an equilibrium model, the influence of inter-carrier competition on service levels and thus on shipper's choices, should not be forgotten.

A different approach has been used by McGinnis et al. (1980) (see also Sharp, 1979; Jones and Sharp, 1979) for the study of multimodal freight transportation opportunities in the Multi-State Transportation Corridor.

In this transportation network, each arc corresponds to an aggregated linehaul facility for a particular mode : highway, rail, water and a TOFC/COFC mode. Additional arcs represent terminal activities within each zone (node) such as loading/unloading, intermodal transfer, and forwarding. For each arc, physical attributes (distance, average speed, daily capacity) are given and operational attributes (transport cost, time and time variability) are computed (see section I). Modal shares are determined with a multinomial logit model, calibrated on historical data using regression analysis. The number of paths available is restricted to

- the best (least-time) all-highway path ;
- the best (lowest shipping cost) all-rail path ;
- the best (lowest shipping cost) all-waterway path (if such a path exists) or the predominant waterway path with short highway/rail connecting segments ;

. the (unique) TOFC/COFC path ;
. an efficient (lowest disutility) multi-mode path.

The transportation assignment problem is then solved by a two-stage procedure applied to each origin-destination-commodity. First, the five paths are generated using shortest-path techniques and, second, the flow to be assigned to each of them is found by means of the multinomial logit model.

The application of this methodology to the Multi-State corridor was quite succesful. The analytical method was able to represent freight movements over the present transportation network in a reasonably accurate fashion and a large number of projects to improve the transportation system (mode by mode, or several modes at once) were evaluated. Sharp and Jones (1981) detail these results and the recommendations of the research team.

It has to be noted, however, that here also the service offered by the various modes is exogenously determined with no feedback from the routing of traffic. Also, the costs used are the costs to carriers to supply the transportation service. No delays, no congestion phenomena, no service reliability factors are included and all the cost formulas are linear. And, finally, the number of paths, both one-mode and intermodal, is much too restricted. It is known that, when congestion is present for example, two or even more paths using the same mode might be necessary to efficiently move traffic.

We now take a closer look at some models representing terminals and their characteristics, especially the delays on the traffic passing through.

Terminals are an important component of a freight transportation system since a significant amount of the total transportation time and cost is imputable to terminal operations.

Rail terminals (yards) have received the most attention and a fairly large number of models (optimization, simulation, econometric, etc...) describing costs, delays, production functions and so on, may be found in the literature (we reviewed some of these models in sections I and V).

For intermodal terminals, almost all the studies have considered container or trailer handling terminals between sea and truck/rail or between truck and rail modes (see the bibliography in Vecellio et al. (1981) or the papers in TRB (1983)) with most of these studies investigating technological issues : equipment, handling procedures and so on. When models are considered, simulation is the approach chosen. Examples of such models may be found in TRB (1983).

The work of Hatzitheodorou (1983) is different. It models the Gate of an intermodal terminal (the subsystem where vehicles stop and containers are loaded/unloaded) as an M/M/S queue, where S represents the number of lanes of the Gate. Introducing the resulting waiting time and queue length in a total operation cost formula, it searches for the "optimal" number of lanes by means of a "trial-and-error" procedure.

Ports are particularly difficult to analyze and relatively few papers on this subject may be found. This is due, first, to the great variety in types of goods passing through ports (solids, liquids, gases, in bulk form, in containers, on pallets, etc.) and the different manipulations implied and, second, to the complexity and variety of port layout, operations and interactions with land use and land and sea transportation.

When models are proposed, detailed simulation models are the rule. Queueing models are often used to estimate delays due to the

various cost operations. Generally, a Poisson arrival process is assumed with a Poisson or Erlang service distribution. Robinson and Tognetti (1973) and, especially, Wilmes and Frankel (1973) critically review the existing port simulation models and queueing submodels and discuss some of the more blatant problems associated with these (aggregation, queueing model specification, the mixed use of subsystems in multi-purpose ports, etc.)

Frankel (1980) took a different approach to port capacity modelling. He views the port as a network of activity and storage links and examines the capacity problem via congestion functions on links. Link flows can be deterministic or stochastic. In its simplest form, the model is a multiple sequential server queueing problem and the author presents an application to the planning of a typical tanker terminal.

This approach using a network representation of the activities of a port seems to present interesting opportunities, especially when the model is embedded into a larger multimodal network for strategic planning.

Queueing models are still a good option for the representation of delays in terminals. However, extreme care is required when defining the service and arrival processes, especially where ports or intermodal terminals are concerned. In fact, it is not always clear what is entering, being served or leaving a terminal. For example, in a port, grain arrives by trucks or train, transits through a silo and is loaded into ships. Several series of queueing models are possible in this situation with very different analytical and computational difficulties.

As far as intermodal systems are concerned, the main conclusion of this review has to be that no satisfactory model has yet been

proposed for the multimode, multicommodity freight transportation problem. The problem might be easier to approach if it is assumed that some global optimum for the whole system is to be found. In this case, the generalization of some of the network rail models described in the next section might be useful. For other cases, however, serious problems arise both at the modelling and algorithmic levels.

We will examine more applications of intermodal transportation systems in the last section of this paper, where we will review some studies of national transportation planning in developing countries.

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V - RAIL FREIGHT TRANSPORTATION

In this section, we briefly review models used to analyze and plan the various operations involved in freight transportation by rail. We do not consider engineering, manpower or maintenance problems. We present the most important and typical modelling approaches and focus on those models more pertinent to tactical and strategic planning.

The rail transportation system may be viewed as a network. Schematically, the arcs of this network represent the line tracks over which traffic moves, while nodes stand for yards locations where a number of operations may be performed on the traffic.

The difficulties associated with planning in this context arise mainly from the complex nature of the operations performed at yards, the need to explicitly consider the flows of carriers (trains) and the multiflows of goods (represented by cars marshalled into blocks) and the ensuing interactions between yard and line policies. A brief review of these policies follows.

Yard policies specify the operations performed on the traffic passing through the yard : reception, inspection, car classification, train assembly, connexion and so on. The main yard activity is the classification (or sorting, blocking, marshalling) operation by which cars are grouped according to their common outbound destination (which may or may not be their final destination). The block thus formed travels without any other modification to this common outbound destination where it is broken up and the cars which are not at their final destination pass through a reclassification. Trade-offs have to be considered between additional costs and delays due to reclassification and the economies of

scale (fewer blocks handled, full train loads, etc.) due to the consolidation of cars into blocks. The decision as to what blocks to build at each yard and as to which cars go into each block is called the classification policy. The blocks are placed on classification tracks and wait for trains. The decision as to which blocks may be carried by each train is called the make-up policy.

Line policies affect the movement of traffic (freight and trains) over the lines of the network. Train routing policies determine what train services will be run on the network, on what routes and with what frequencies. Timetables (where used) specify the arrival and departure times at each yard on the train route. Track priority rules govern meets and overtakes on tracks. Line policies also specify empty car and locomotive flows so that their avalability is ensured when needed. Finally, traffic routing policies determine the routing pattern for the traffic moving between each origin-destination pair (this may also vary according with the category of goods to be moved) : the train sequence used to travel and the yards where cars are reclassified.

Some of these policies impact the whole rail system and interact among themselves as well as with other yard and line policies. Train and traffic routing, empty car and engine distribution and network-wide blocking policies are in this category.

In the context of rail planning, strategic decisions involve investments in the long term. Changes in the network structure, location, expansion or abandonment of facilities, broad routing decisions are strategic issues. We do not know of many models designed specially for these problems. LeBlanc's model (1976) aimed at the optimal design of a rail network is a unique example. In this model, LeBlanc minimizes

a combined line shipping and investment/maintenance cost to determine, for each line, the optimal flow and shipping cost parameter. The cost parameters reflect the quality of the line : the lower the shipping cost, the higher the quality of the track. The model is then :

$$\text{Minimize} \quad \sum_{ij} [c_{ij} \sqrt{x_{ij}} + b_{ij} (c_{ij} - \bar{c}_{ij})^2 + d_{ij}]$$

$$\text{Subject to} \quad \sum_{j} x_{ij} \leq b_i \qquad \text{all source nodes } i$$

$$\sum_{i} x_{im} = D_m \qquad \text{all demand nodes } m$$

$$\sum_{i} x_{ik} = \sum_{j} x_{kj} \qquad \text{all transshipment nodes } k$$

$$c_{ij} \leq \bar{c}_{ij}$$

$$0 \leq x_{ij} \leq u_{ij} \qquad \text{all lines } (i,j)$$

where

c_{ij} : shipping cost parameter for line (i,j)

x_{ij} : flow on arc (i,j)

$\bar{c}_{ij}$: cost parameter for line (i,j) corresponding to a minimum maintenance level (secondary track)

b_{ij} : investment cost for line (i,j)

d_{ij} : maintenance cost for line (i,j)

u_{ij} : upper bound on the flow of the line (i,j)

S_i : supply at node i

D_m : demand at node m

This non-convex, non-concave problem is transformed (by means of an explicit formula linking the values of the cost parameters to those of the flow variables) into a network flow problem with concave costs, solved by an efficient algorithm based on successive linearization of the objective. The algorithm has been tested on a number of random generated problems with good results.

A much larger number of models have been proposed for problems classed as operational in rail planning : dispatching policies (in yards, over a line, etc.), timetable setting, empty car distribution, engine scheduling and so on. These problems, dynamic in nature, often dealing with day-to-day activities, are not, however, within the scope of this review. We refer the interested reader to the survey paper by Assad (1980a).

The purpose of tactical planning is the efficient and rational allocation of existing resources in order to improve the performance of the system. Tactical models may be used to generate and evaluate new operating strategies or to assess the effects of changes in existing policies. Thus, they are used as evaluation tools in strategic decision processes. Network models generally address tactical issues : train and traffic routing, global blocking and make-up strategies.

We now review some important models and formulation approaches, which may be used in tactical and strategic planning. Simulation models are not within the scope of this paper and therefore are not covered. Note however that they are used by the railways, especially as detailed evaluation tools. For additional information, the interested reader may consult the survey paper by Assad (1980a) and also Khan (1979) and Baker (1977).

Yard models analyze the operations of a given classification yard or of one of its subsystems and are specially concerned with the delays imposed on cars passing through the various subsystems of the yard : reception and inspection, classification, connexion, train assembly, outbound inspection and departure. Generally, each subsystem is treated individually, the yard model specifying the relationships among them.

Classification, assembly and connexion usually are bottlenecks in the system and queueing models have been proposed to represent them.

Petersen (1977a) proposed M/G/S models for the classification and assembly operations, where M denotes a Poisson input, G a general service time distribution and S is the number of service channels. He discusses how the form of the service time distribution varies according to the type of yard and in a companion paper (1977b) shows how the service times are related to the configuration of the yard, the available resources, the train marshalling policy and the traffic passing through the yard. For connection delays, the proposed model is a $M/E_k/1$ (bulk service) queueing model, where E_k stands for an Erlang distribution of order k. Those models have been validated on data from the Canadian National and Canadian Pacific rail systems.

Turnquist and Daskin (1982) also propose batch queueing models for yard operations : a M/G/1 batch arrival model for classification delay and a $M/G^{\infty}/1$ infinite batch size service model for connection delay. The authors also examine the variances of the waiting times, provide "best" and "worst" case bounds and discuss the correlations between the delays while computing the total yard delay.

Line models analyze train movements in order to evaluate train performance and line capabilities, different track facilities, or dispatching rules and procedures.

Analytical models use algebraic expressions for the transit time of each type of train service as a function of the intensity of train traffic, train operating characteristics, track configuration and dispatching rules used. The degree of detail varies with the intended use of the model : thorough operating analysis of the line or an evaluation submodel for over-the-line delays. Typical of these models are those by

Frank (1966), Elbrond (1978), Petersen (1974, 1977d) and English (1977, 1978). Note that Elbrond's model has already been applied in Brazil (Elbrond, 1970).

Network models integrate line and yard activities in order to answer one or more of the questions raised during the tactical planning process. They generate and evaluate the network-wide effects of a large number of operational strategies with respect to some objective function, usually involving both operating costs and delays.

The "Railcar Network Model" developed at the CIGGT at Queen's University by Petersen, Fullerton and others (1975b) is a prime example of this class of model. The object of the model is to find the optimal traffic routing minimizing total car delay : the sum of yard and line delays. In yards, the average delays are derived by means of queueing models as a function of the traffic flow through the yard. Similarly, Petersen's over-the-road model gives the average time to traverse a given link as a function of the train flow on that link. The number of trains to be run is determined from the traffic flow using a constant number of cars/train ratio. If the delay functions are all convex, the problem has the structure of a multi-commodity flow problem with convex costs and it is solved by a primal-dual algorithm (Petersen, 1975a) based on successive linearizations of the objective. Schiwier et al. (1976) document the computer codes for the models. Although tested in the context of Canadian railways the model is not actually in use.

Assad (1977, 1980a) suggests a network model that integrates the routing and make-up decisions. Its goal is to reduce the delays due to congestion in yards by means of direct trains bypassing the intermediate

yards on their routes. Assad uses a route structure defining all the direct services for the problem at hand. The traffic travels on that structure, connecting when the destination of the service is not the traffic destination. Every time a service reaches its destination, the traffic traveling on it goes through a classification procedure. Different "fixed-charge" type formulas are suggested for the classification delay as a function of the yard throughput and the train composition. The resulting model has the structure of a multicommodity mixed-integer flow problem with certain nonlinearities in the objective function. An efficient solution technique has not yet been proposed for this model.

Crainic (1982, 1984a) proposes a network model that integrates the train and traffic routing decisions together with rough blocking and make-up policies. Its goal is to generate global strategies to reduce the total operation and delay cost of the system. It uses a service network defining the feasible train services : their routes, intermediary stops and modes. For each traffic-class (an origin-destination-commodity-combination), itineraries specify feasible journeys for the traffic : the service path followed and the sequence of yards used for classification. Classification delays are a function of the yard throughput (via queueing models) and the particular block the cars are sorted into; connexion delays are a function of the frequency of the service chosen and of the type of service (regular or following a certain probability distribution) ; over-the-road delays are a function of the total train flow on the link and track configuration. The model has the structure of a nonlinear mixed integer multicommodity flow problem in arc-chain formulation and is solved (Crainic, 1984b) by a heuristic based on decomposition and column generation techniques. The model has been tested on data from the Canadian National railways and good results are reported.

The blocking model of Bodin et al. (1980) aims to determine network-wide classification policies to minimize total delay : a sum of accumulation and connexion delays, processing time for cars and over-the-road travel time. Continuous variables x^p_{ijk} give the number of cars shipped from yard i to yard k along path p to be reclassified at yard j on that route and interact with integer variables y^q_{ij} that specify if a block is formed at yard i for yard j along path q. Bounds are imposed on the number of cars in a block and on the total number of cars processed through a yard. Additional constraints reflecting particular practices at the railroad under study further complicate the problem. So also does the form of the accumulation delay function : non-continuous piece-wise linear. This function is approximated by a continuous piece-wise linear function and the problem is solved by a heuristic based on successive relaxation of the original problem. Bodin and Berman (1979) describe the solution technique and the results of a case study involving 33 yards and a mixed integer problem with 1500 constraints, 1000 binary variables and 5000 continuous variables.

As may be seen from this brief review, no practical models have been designed to address strategic issues in freight transportation by rail (at company level). To our knowledge, current practice involves the heavy use of detailed simulation models as support to traditional management methods. As for the design model of LeBlanc (1976), this is a theoretical model, using a very simple and asepticized view of rail operations.

Models developed for tactical planning might therefore be more useful to the project.

A great deal of attention has been and will continue to be devoted to yard operations. Although the precise form of the models vary, the consensus seems to be that queueing models are the best mean of representing yard delays.

Note, however, that in the Brazilian context rail operations are simpler and yard operations are less important that in North-America : the traffic usually moves by unit trains (a one commodity direct train) which means little classification and even less reclassification of cars. Consequently, simple queueing models might be sufficient, especially if they are to be included in a more general rail model.

The same remark is also valid concerning line models. Specific line models, like most of those mentioned, are well suited to analyze the capacity and operations of a rail line but they generally include factors such as the detailed procedure for train meetings (slowing, stoping, accelerating, etc.), the probabilities of train meets and overtakes, and some description of the signalization system. This is too detailed for strategic planning where only an aggregated measure of capacity is needed. The factors that, in our opinion, should be included are the intensity of the train traffic and some characteristics of the line (length, usual running speed, number of passing points).

Using such aggregate line and yard capacity/delay measures, network tactical models also represent good evaluating tools for strategic planning. In this respect, the model of Crainic et al (1984a,b) is presently the most comprehensive and flexible. But, considering the particular operating policies of Brazilian railways (most of the traffic on full length unit trains), it might be sufficient (and certainly easier)

to implement a model which follows the philosophy of the Railcar Network Model and explicitly considers only the flow of cars, while the flow of (full) trains is derived afterwards.

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VI - NATIONAL TRANSPORTATION PLANNING IN DEVELOPING COUNTRIES

Our goal here is to briefly review the objectives and main methodological approaches of some important studies in national transportation planning in developing countries.

First, note that relatively few such studies exist and, with the exception of the Sao Paolo study, none of the existing studies has the same type of objective as the current project. Finally, note that, in general, a "one shot" approach has been taken, while the techniques used are not very sophisticated.

The interested reader may consult the book by Kanafani and Sperling (1982), especially for the extensive bibliography which it contains. Howel (1979) gives an interesting overview of national transportation studies that have been documented during the past twenty years, together with a critique of their methodologies. Some of the following summaries are based on that publication.

Colombia - 1962

The now famous "Harvard Model" was developed to study investment alternatives in the Colombian Transport System (Roberts et al., 1968, Kresge and Roberts, 1971). The main task of the study was to select, rank and phase a set of proposed projects and to allocate a given budget to these projects to maximize national profit. Simulation was the approach used. At the core of the study is a macro-economic model using input-output tables and transportation submodels for each mode. Generalized costs (cost of waiting, travel time, uncertainty, etc.) were used to determine modal choice by a minimum path routine. Linear programming or gravity models, according to the characteristics of each commodity

(passengers are considered as a commodity), were proposed to solve the flow distribution problem. The overall model was run year by year for each transport alternative. The scarcity of adequate data has been one of the major problems of this application.

Dahomey - 1969

This study (Lea et al., 1968; Miller, 1970) examined the economic impacts of several possible highway and railway development programs.

Two computer programs were developed. From roughly extrapolated socio-economic data, the program TRANS produced flows and costs by vehicle type for each link plus overall performance measures. Linear programming was used for the distribution of commodity flows. Commodities were assigned to shortest paths. Only transportation costs were considered. OPT analyzed each link and selected the investment alternative which would minimize the value of the total cost for the link, given the present traffic. The improved network was then introduced in TRANS. The process was stopped after a few iterative runs of these two programs.

Venezuela - 1974

The aim of the study was to provide technical guidelines for political decisions in the context of a transport investment program.

From socio-economic data forecasts, transport demand forecasts (for three different years) were obtained for each link of the road and air networks as well as for ports. Multilinear regression analysis was used. Projects for ports, airports and road and air links were examined by means of cost-benefit analysis. An economic evaluation of railway and barge systems wss also performed, leading to the conclusion that both modes were not profitable.

Sudan - 1975

The Sudan transport study (ADAR, 1975, Harral and Henneman, 1970) was intended to assist and improve the political decision making process both for a coordinated national transportation plan and for the limited objective of meeting urgent needs in the transportation sector.

A composite scenario of a desirable future for the country was developed and tested through a macro-economic model. Passenger flows were then forecasted for every link, by means of modal and regional growth rates applied to base-year values. Freight flows were computed by distributing surpluses/deficits per commodity and region using a linear progamming model that minimized total distance. The modal split was estimated by inspection according to local physical constraints and transport costs, time reliability, etc.

Gaps in the transportation system were then identified by comparison, while the level of new or improved links was determined by a cost/benefit analysis.

Prioritization was carried out by considering the socio-economic impact of the projects in their regions and of the regions in the state.

Iraq - 1975

In contrast with the preceding studies, the Iraq (1975) study was not intended to propose new development projects but was aimed at evaluating and prioritizating a set of projects presented by different local agencies, with the development of a five-year transport plan as a goal.

The levels of basic economic sector activities were forecasted via regression analysis. Each transport project was assessed on engineering and economic grounds. These projects were then aggregated and "physical networks" were built for each mode. Intermodal compatibility was examined using "engineering" judgement.

Flow forecasts for goods and passengers were obtained by spatial distribution of surpluses and deficits using linear programming. Flows were allocated by mode on a cheapest mode basis.

Comparing the resulting "hypothetical" network needed to satisfy this forecasted demand to the "physical" network, the gaps and insufficiencies of the network were identified. Prioritization was conducted according to cost/benefit and budgetary criteria, as well as a likelihood of completion and successful operations analysis, and the relationship with national objectives.

Sao Paulo, Brazil - 1977-1978

The Sao Paulo transport study (Echenique, a,b,c,; Sondotecnica, a,b; Williams and Echenique, 1978; Dunford, 1978) was aimed at testing and evaluating alternative transport policies with three major objectives in mind : (i) to improve the efficienty of the State's transport sector and especially the railways; (ii) to improve the distribution of benefits arising from transport policies in favour of the poorest regions of the State; (iii) to reduce the rate of growth in the metropolitan region of Sao Paulo.

Input/output analysis was used, in a first submodel, to predict the final demand for each commodity group in each zone. Interzonal flows of passengers and goods were then obtained using a gravity, single constrained model. Transportation costs and times were both used in the objective.

In a second submodel, these commodity flows were assigned to particular modes and routes via an iterative scheme, using transportation costs and times as well as route capacities iteratively adjusted to account for congestion until equilibrium was reached in terms of supply and demand.

The model was used to simulate alternative policies for the years 1980, 1985 and 1990, using 1975 as a base year. Presently, this model is not in use.

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